Development of a Prototype Nickel Optic for the Constellation-X Hard X-Ray Telescope: IV

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ABSTRACT

The Constellation-X mission planned for launch in 2015-2020 timeframe, will feature an array of Hard X-ray telescopes (HXT) with a total collecting area greater than 1500 cm^2 at 40 keV. Two technologies are being investigated for the optics of these telescopes, one of which is multilayer-coated Electroformed-Nickel-Replicated (ENR) shells. The attraction of the ENR process is that the resulting full-shell optics are inherently stable and offer the prospect of better angular resolution which results in lower background and higher instrument sensitivity.

We are building a prototype HXT mirror module using an ENR process to fabricate the individual shells.This prototype consists of 5 shells with diameters ranging from 15 cm to 28 cm with a length of 42.6 cm. The innermost of these will be coated with iridium, while the remainder will be coated with graded d-spaced W/Si multilayers.

The assembly structure has been completed and last year we reported on full beam illumination results from the first test shell mounted in this structure. We have now fabricated and coated two (15 cm and 23 cm diameter) 100 micron thick shells which have been aligned and mounted. This paper presents the results of full beam illumination X-ray tests, taken at MPE-Panter. The HEW of the individual shells will be discussed, in addition to results from the full two shell optic test.

Keywords: X-ray Telescopes, X-ray optics, multilayers, electroformed optics

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1. INTRODUCTION

The Constellation-X Mission,[1,2] scheduled to be launched in 2015-2020 timeframe, consists of 2 telescope systems: the spectroscopy X-ray telescope (SXT)[3] and the hard X-ray telescope (HXT).[4] This paper, which is the fourth of a series of papers we have presented to SPIE since 2003, discusses one approach to the fabrication of the HXT optics and presents a progress update on recent work.

The Smithsonian Astrophysical Observatory (SAO), the Marshall Space Flight Center (MSFC) and the Brera Observatory, Italy (INAF-OAB), are collaborating to design and build a prototype optic for the HXT of Constellation-X. Our approach is to electroform nickel shells of full revolution which meet the requirements of the HXT. The use of full-shell optics which are inherently stable, offers the prospect of better angular resolution and therefore lower background and higher instrument sensitivity.[5] This technology was developed for XMM/Newton which achieved a resolution of 15 arcseconds. The thickness of the XMM mirror shells varied as a function of diameter according to : thickness (mm) = diameter (mm) x 1.5 x 10^{-3}, and ranged from 0.47 - 1.0 mm. The stringent mass allocations of X-ray astronomy missions such as Constellation-X place a tight mass constraint on the telescope optics. It was necessary to improve upon the electroforming process to fabricate much thinner, lighter weight shells while not degrading the figure. At the same time, the energy band of the HXT required multilayer coating on the inside surface of the shells, compared with the single layer metallic gold coatings of previous missions. Therefore many developments had to take place to move from the current status of the XMM telescope to meet the requirements of future NASA missions such as the HXT of Constellation-X.

2. PROTOTYPE

Our goal is to fabricate, integrate and test a 5 shell prototype optic which spans the full range of diameters planned for the HXT of Constellation-X.

The prototype we have designed to meet these tests is shown in an engineering drawing in figure 1 and consists of 5 shells 42.6 cm long with diameters 15, 23, 25, 27 and 28 cm with a focal length of 10 meters . The inner-most shell will be iridium coated; the four outer shells will have W/Si multilayer coatings. Given the 10 m focal length of Constellation-X, the HXT shells with radii $\leq$ 8 cm will have graze angles of $\leq$ 0.12 degrees. At such small graze angles, a single metallic coating, such as iridium, will yield reflectivities as high as or higher than that of W/Si multilayers for energies up to 40 keV. Beyond this graze angle, the reflectivity of a single metallic layer quickly falls to zero and multilayer coatings are necessary to achieve any reasonable effective area.

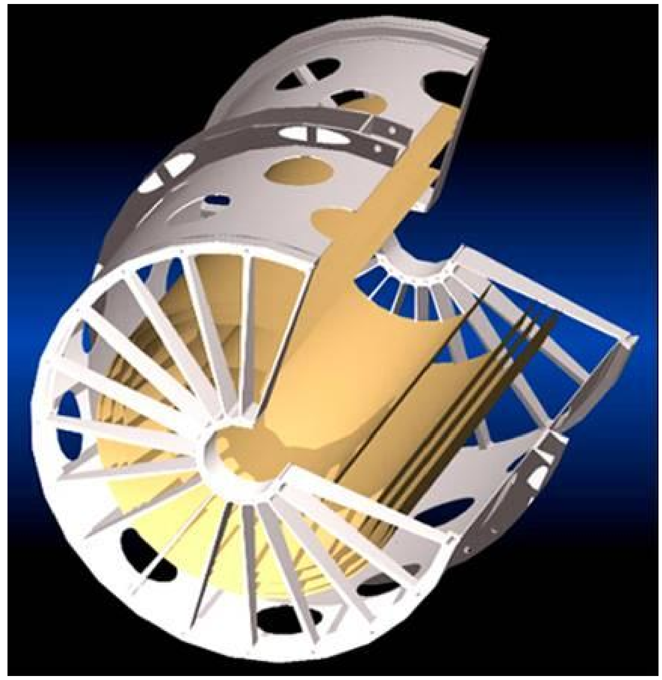

Figure 1. Engineering CAD representation of prototype with 5 mirror shells shown in the telescope structure.

Therefore, our present design includes coating the inner shells with iridium and the outer shells (radii $\geq$ 7 cm) with W/Si multilayers. This design yields a greater effective area at 40 keV than if all shells were coated with W/Si multilayers and is also faster and easier to complete due to the single layer coatings on the inner shells.

3. MULTILAYER COATING FACILITY AT SAO

The multilayer coating facility at SAO is equipped with two DC magnetron sputtering chambers which are shown in figures 2 and 3. The first, smaller chamber was built to grow multilayer films on flat two inch substrates. The majority of our research and development work using different material combinations and using various coating parameters to investigate the best multilayer films for hard X-ray astronomy telescopes was carried out in this chamber. It has relatively low cost targets and has a quick turn-around for completing more than

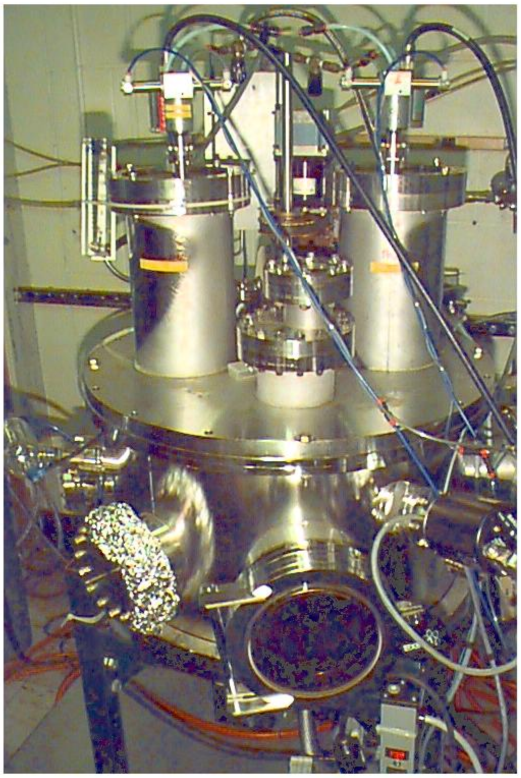

Figure 2. `photograph of SAO R&D DC magnetron coating chamber. The chamber is 60 cm diameter and 40 cm in height`

Figure 3. `SAO DC magnetron coating chamber with an early test INAF-OAB shell, 200 microns thick, 60 cm long, 30 cm diameter.`

one test coating in a day. The second chamber (figure 3), was designed specifically to coat flight size optics. The chamber was designed with long thin cathodes and a computer-controlled rotation stage to allow for internal coating of integral (or segmented) cylindrical shells. The rotation stage built into the chamber is computer controlled to rotate the optics about the linear sputter targets in order to apply a uniform coating. The cathodes are 60 cm in length, designed to accomodate the HXT optics. The coated electroformed full shells discussed below were all coated in this chamber. Several earlier papers discuss the details of the chambers.[6–8] We are one of two U.S. groups[6,7,9] who have spent considerable effort over the past several years to study multilayer film coatings specifically for the HXT of Constellation-X. Much of our development work on different multilayer coatings of interest in X-ray astronomy has been described earlier.[7,10] Although there is still much work to do to develop coatings for higher energies ($\geq$80 keV), it has been shown[6,9] that multilayer coating technology for the energy band up to 70 or 80 keV is easily achievable.

Although we have yet to see a hard X-ray multilayer telescope in orbit, many multilayer films have been tested at synchrotron beamlines where beam energies up to and above 100 keV are available. The data show that the response is as predicted.[6] In addition, stability studies[11] have been carried out to show that these multilayers are stable over the time period necessary for a satellite mission. The hard X-ray telescope on Constellation-X will utilize multilayer coated optics to probe this relatively uncharted energy band.

4. PROTOTYPE TELESCOPE WITH THIN WALL ELECTROFORMED MIRROR SHELLS

We are building a prototype hard X-ray telescope with an angular resolution of less than one arcminute.The telescope contains 100 micron thick integral mirror shells that are produced by the electroforming process.

Two different processes have been developed. INAF-OAB extended the development of the electroforming process used by XMM which used a gold film on the mandrel as a release agent. The OAB process has produced 130 micron thin multilayer coated shells with 25 arcsecond resolution, as measured in full-illumination X-rays. The second process was developed at MSFC as an outgrowth of a NASA SR&T program for the development of replicated optics (B.Ramsey, P.I.) for the HERO balloon program. HERO's needs are met with small diameter 250 micron thick shells. For our requirements of thinner, larger diameter and lower mass shells, Ramsey et al.[12] developed a new process using a stronger NiCo alloy to form lighter mass shells. We have succeeded in obtaining thin, 100 micron shells with typical resolutions of 13-16 arcseconds as determined from metrology measurements. Several of these are shown in figure 4. After each electroformed shell is coated, it must be aligned in the telescope structure before X-ray testing can take place.

Figure 4. coated MSFC shells: 42.6 cm long, 23 cm diameter, 100 microns thick.

5. TELESCOPE STRUCTURE AND ALIGNMENT OF THE SHELLS

Each shell is mounted into the HXT telescope integration structure before it is inserted into the X-ray pipe at the Panter Facility for full beam illumination measurements. The integration structure provides support for the optic, retaining the figure and providing a surface for manipulation of the optic once it is in the chamber. This structure, shown in figure 5, was constructed at INAF-OAB and was designed to be used as the outer structure for the HXT flight optic. The 20 arm spider to which the individual shells are attached can be seen at the top of the structure and there is an identical spider at the bottom. Each spider arm has grooves machined into it for the different diameter shells. Part of the integration process involves epoxying the shell at each spider point after the shell is properly aligned.

Figure 5. Photograph of HXT telescope module in UV test facility at INAF-OAB. Two shells fabricated at MSFC, 15 cm and 23 cm diameter are mounted in the structure. The length of the shells is 42.6 cm. The spider assembly for fixturing the individual shells can be seen on top.

The vertical UV alignment facility at INAF-OAB was used to align the shells and mount them into the integration structure. This UV system can be used to align the mirror shells with the optical axis, but because of diffraction of UV due to the small projected area of grazing incidence telescopes, final angular resolution measurements must be taken at a full illumination X-ray facility such as the MPE-Panter Test Facility, which provides a quasi parallel large diameter X-ray beam. Several individual shells were mounted in this structure and tested at Panter during the development phase. In the following section we discuss results from two of these tests: one with only a single 23 cm diameter multilayer coated shell in the fixture, and a second test where two confocal coaxial mirror shells were mounted in the structure. This latter test provided data on the individual shell response and also on the response of both shells together, which tests our ability to co-align these thin shells.

6. X-RAY TESTING OF SHELLS AT MPE PANTER X-RAY TEST FACILITY

6.1. The Setup

The MPE Panter X-ray test facility has been described previously.[13–15] Here we only briefly list the setup used in our testing.

Several different anodes mounted on a target wheel were used to provide characteristic X-ray lines from 0.28 keV to 8.05 keV. Coupled with a ROSAT type PSPC detector, this combination is useful for measuring encircled energy and HEW. Figure 6 is a photograph of the spider module and shell in the X-Ray pipe. The module is shown fixtured to the Panter manipulator mounted at the entrance to the testing chamber. X-rays travelling down the pipe reflect off the optic and are focused on the detector mounted in the focal plane (not visible in this photo). The radial ribs that can be seen in the figure are part of the spider structure used to fixture the shell.

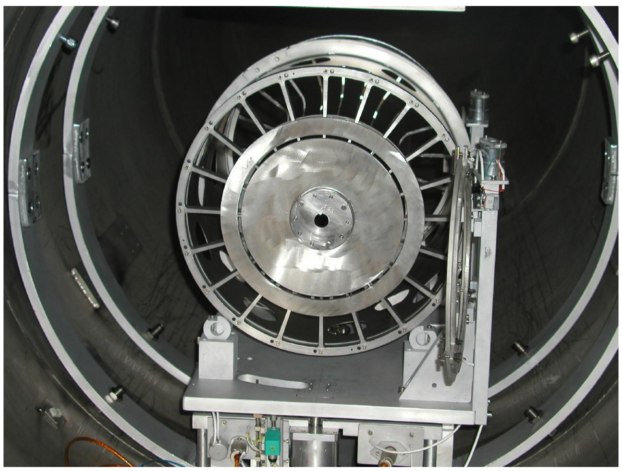

Figure 6. Photograph of HXT telescope module in X-ray pipe at Panter Facility. The two plates used to shutter the individual optics can be seen.

6.2. The Data

Last year (SPIE '05) we reported data for the first fully-integrated MSFC NiCo replicated shell coated with W/Si multilayers. The shell was 150 microns thick, 42.6 cm long, 23 cm diameter with a 10 m focal length. The HEW we reported for the shell was $\approx$ 30 arcseconds, well below the 1 arcminute requirement of the HXT. One of our goals for this year was to fabricate even thinner shells, 100 microns thick, while keeping the same (or better) figure.

Several 100 micron thick shells were fabricated and coated over the past year. After fabrication at MSFC, a vertical long trace profilometer was used to measure the figure of the inner surface of the shells; circularity was measured using a coordinate measuring machine and an atomic force microscope was used for micro-roughness measurements. Performance prediction for the shells was then be made based on results of these measurements. All coated shells discussed here were coated with the same multilayer recipe: a graded-d W/Si with N=95 as follows: the bottom N=75 bilayers were (Si=22-33 Å; W=12-17 Å) followed by a deposition of N=20 bilayers of (Si=30-100 Å; W=21-58 Å). The coating was chosen to give approximately 30% reflectivity at 20 keV, for the finite distance of the Panter source. The finite source distance coupled with the 10 meter focal length yield a graze angle of 0.27 degrees, considerably larger than it would be for an infinite source distance.

Two different sets of X-ray tests are reported here: the first is for a single 23cm diameter multilayer coated shell, the second is for two co-aligned shells - one 15 cm diameter and one 23 cm diameter. Two shutters mounted on the telescope assembly gave us the ability to illuminate each shell inividually to measure the characteristics of a single shell and, with both shutters open, to measure the combined properties of the two co-aligned shells. Table 1 lists the half energy widths measured for each of four different energies using the PSPC detector. Column 2 of table 1 presents the measured HEW for the 15 cm diameter shell with the 23 cm shell shuttered; column 3 of the table gives the HEW data for the 23 cm shell with the 15 cm shell shuttered; and finally, column 4 of the table presents the measured HEW data for the combined, co-aligned 15 cm and 23 cm shells. As shown, the HEW for the 15 cm shell alone was $\approx$ 29 arcseconds, the HEW for the 23 cm shell alone was $\approx$ 38 arcseconds and the combined HEW was 35 arcseconds. We know from XMM and HERO experience that the major contributor to the finite angular resolution is not errors in co-alignment of the mirror shells but rather is the figure error of a single shell. Because we can align the axes of the mirror shells with much greater precision than the width of their resolution function, we don't expect the resolution to degrade with the addition of more shells. The fact that the HEW for both shells is no worse than that of the individual shells is consistent with the shells being well aligned. The 23 cm shell mounted for the co-alignment test was one of the earlier test shells fabricated, and is not representative of more recent typical 100 micron thick shells. The last column of table 1 presents the

HEW for a 2nd, more typical 23 cm shell which was mounted and tested. The HEW of this shell is ≈ 31 arcseconds.

Table 1. Measured half energy widths for assembly with two co-aligned shells: 15 cm and 23 cm diameter; shells were fabricated at MSFC, coated at SAO and aligned at INAF-OAB. Data are presented for each shell individually and also for the two shells combined; the last column is the measured HEW for a 2nd 23 cm shell which was measured separately (see text).

Energy (keV)	HEW (arcsec) 15 cm	HEW (arcsec) 23 cm	HEW (arcsec) both	HEW (acsec) 23cm
4.51	28.9	37.8	32.5	29.6
5.41	28.7	37.6	33.7	–
6.40	29.2	39.0	34.8	30.5
8.05	29.5	38.9	35.5	31.2

Metrology of the 100 micron thick shells fabricated at MSFC predicts a figure between 13 - 16 arcseconds for all of the above shells. After alignment and mounting in the telescope assembly, the measured HEW for these same shells is ≈ 30 arcseconds. We believe this is due to distortion caused by our method of installing the mirror shells. Due to the extreme thinness of the shells, two accurately machined stainless steel rings are used to hold the shape of each shell as it is being epoxied into the spider. After the epoxy is cured, the rings are removed. It is possible that the weight of the rings introduces a deformation in the shell which then relaxes when the rings are removed. By reducing the mass of the rings, we expect to achieve a final figure which is much closer to the 13 - 16 arcsecond figure predicted by the individual shell metrology. Work is now underway to implement these improvements.

7. SUMMARY AND FUTURE WORK

Over this past year we have fabricated and tested in full-illumination X-ray beam two co-aligned multilayer coated 100 micron thick nickel shells. Results show a measured spatial resolution of 35 arcseconds HEW for the co-aligned pair, which more than meets the one arcminute specification for the HXT. In addition, we have a plan which we believe will improve this resolution to better than 20 arcseconds. We are now prepared to fabricate a prototype with enough shells to sample the entire radial range of a typical HXT telescope. Future work includes completion of the remaining 3 mandrels and fabrication, integration and testing of a complete set of 5 coated shells in the full beam illumination X-ray pipe at MPE Panter. In addition, we are prepared to carry out the tests to put this technology at a TRL-6 readiness level.

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